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MEMORANDUM REPORT NO. 1901

MILLIMETER WAVE RADIO METRIC DETECTION OF
TARGETS OBSCURED BY FOLIAGE

by

Richard A. McGee

January 1968

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Richard A. McGee

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland

January 1968

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BALLISTIC RESEARCH LABORATORIES

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JANUARY 1968

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Ballistic Measurements Laboratory

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RDT&E Project No. 1M523801A286

ABERDEEN PROVING GROUND, MARYLAND

BALLISTIC RESEARCH LABORATORIES

MEMORANDUM REPORT NO. 1901

RAMcGee/sjw
Aberdeen Proving Ground, Md.
January 1968

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ABSTRACT

The problem of passive detection by millimeter wave radiometry of metallic targets obscured by foliage and other vegetation is defined and discussed. A model of the foliage obscuration situation is presented and evaluated on the basis of data collected in a field measurement program. Results obtained show the millimeter wave radiometric obscuration to be greater than the optical obscuration. Curve fitting techniques indicate a quadratic relationship between radiometric and optical obscuration; hence, the maximum range of a radiometric system will be reduced linearly with optical obscuration instead of theoretically with a square root relationship. Further refinements of the model are discussed and are to be included in a general foliage penetration model to be evaluated at a later date.

TABLE OF CONTENTS

	Page
ABSTRACT	3
I. INTRODUCTION	7
II. THEORETICAL CONSIDERATIONS	8
A. Planck's Law	8
B. The Radiometer Range Equation	9
III. TEST PROCEDURES	10
IV. FIELD MEASUREMENTS AND DATA REDUCTION	12
V. RESULTS AND DISCUSSION	17
DISTRIBUTION LIST	25

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I. INTRODUCTION

Target detection in a foliage environment is a difficult task. Passive detection with radiometric techniques depends on the detection of radiated energy (or lack of it) in the millimeter wave region of the electromagnetic spectrum from a metallic target obscured by foliage. An opaque object between the target and the radiometer attenuates the radiated energy from the target. The obstructing object also contributes energy proportional to its effective temperature and emissivity. The ability to distinguish the contrast between a target and its background is reduced in the event of foliage obscuration of the target.

In the course of several measurement programs with millimeter wave radiometers at the Ballistic Research Laboratories (BRL), the effect of sparse foliage located between the radiometer and target was to degrade the target-background temperature contrast more than the radiometric range equation would predict. The apparent blockage or obscuration of radiometric reflected sky energy was consistently more than was indicated by the optical blockage.

A series of measurements were taken to investigate the relationship between blockage of radiometric reflected sky energy and optical blockage of a target by foliage. The data from the measurements were used to derive an empirical relationship which could be used in the radiometric range equation to provide more realistic performance standards for radiometric systems.

Reduction of radiometer range occurs with obscuration of the target by foliage. This reduction of range depends on the radiometric blockage. This report examines the dependency of the range reduction and radiometric blockage on optical obscuration.

II. THEORETICAL CONSIDERATIONS

A. Planck's Law

Radiometry may be defined as the technique of measuring electromagnetic energy considered as thermal radiation. An object heated to a temperature above absolute zero will radiate electromagnetic energy in accordance with Planck's law

$$F_v = \frac{2\pi h v^3}{c^2} \frac{1}{\exp(hv/kt) - 1} \quad (1)$$

where F_v = power emitted from unit area perpendicular to direction of emission in units of $\frac{\text{watt-second}}{\text{cm}^2 - \text{sterad}}$

h = Planck's constant in 6.62×10^{-27} erg-sec

v = frequency in hertz

c = velocity of light in 2.997×10^{10} cm/sec

k = Boltzmann's constant in 1.38×10^{-16} erg/deg

T = absolute temperature in $^{\circ}\text{K}$.

If $h\nu \ll kT$, which is usually the case for millimeter and longer wavelength signals, Planck's law reduces to the Rayleigh-Jeans approximation

$F_v = \frac{2k\pi T v^2}{c^2}$. The power available at the terminals of an isotropic linearly polarized antenna is $P_a = kT\Delta\nu$ which is the familiar kTB formula used in the noise analysis of amplifiers.

A body upon which wide-band electromagnetic radiation impinges may transmit, reflect, or absorb certain spectral portions of this radiation. An object which absorbs all of the incident radiation is known as a black body. Thermal power received by a radiometer is a combination of three factors:

- (1) Actual molecular target temperature and emission
- (2) Reflected sky temperature
- (3) Path attenuation and emission contributions.

Neglecting path contributions, the target contrast with background is defined as

$$\Delta T = \epsilon_B T_B - \epsilon_t T_t + (\rho_B - \rho_t) T_s \quad (2)$$

where ϵ_B = emissivity of background, ratio of emission temperature to thermal temperature

T_B = thermal temperature of the background, $^{\circ}\text{K}$

ϵ_t = emissivity of target, ratio of emission temperature to thermal temperature

T_t = thermal temperature of target, $^{\circ}\text{K}$

ρ_B = reflectivity of background, equivalent to $1 - \epsilon_B$

ρ_t = reflectivity of target, equivalent to $1 - \epsilon_t$

T_s = temperature of sky, $^{\circ}\text{K}$.

Equation (2) shows an apparent temperature differential may exist between a target and its background with both at the same thermal temperature if the reflectivities differ. Since $\rho_t \approx 1$, for metals, $\epsilon_B \approx 1$ for vegetation and noting that $\epsilon = 1 - \rho$, the temperature of the target is nearly equal to T_s while the radiometric temperature of the background is nearly equal to T_B ; therefore $\Delta T \approx T_B - T_s$. The temperature of the sky is typically about 30°K at an 8.6-mm wavelength while the background temperature of vegetation is in the vicinity of 290°K . Typically, millimeter wave radiometric temperature contrasts between a ground-based target and background are approximately 200°K . This temperature contrast can be used to detect targets in clutter by making radiometric measurements of temperature.

B. The Radiometer Range Equation

The range equation* for a Dicke radiometer may be expressed as

$$R^2 = \frac{\pi S_t (D/1.5)^2 \Delta T}{2 L^2 (S/N) (F + 1) T_o} \left(\frac{\Delta f}{2B} \right)^{1/2} \quad (3)$$

* S. Chang, "A Study on Microwave Radiometry." Frankford Arsenal. Memorandum Report W53-4-1, July 1962.

where S_t = target area in square feet

D = antenna diameter in feet

ΔT = temperature contrast between target and background in $^{\circ}\text{K}$

L = atmospheric loss

λ = wavelength in feet

S/N = signal to noise ratio

F = radiometer noise figure

Δf = predetection bandwidth

B = postdetection bandwidth

T_0 = radiometric temperature of background

R = range in feet.

Any foliage between the target and radiometer has the effect of reducing the range at which the target can be discriminated from the background. Effectively, this range reduction occurs because the area of the target seen by the radiometer is reduced. Therefore, though range is proportional to $\sqrt{S_t}$ in the range equation, measurements indicate that the range reduction is consistently greater than indicated by the $\sqrt{S_t}$.

III. TEST PROCEDURES

A measurement program was initiated in order to investigate the relationship of optical obscuration to radiometric obscuration. The radiometer used was a 35 GHz Radiometric Tracking-Measuring System, K.S.D. No. 401 modified by BRL to operate in the Dicke mode. This system has an PMS temperature sensitivity of 0.4°K for a 0.3 sec postdetection integration time constant. The antenna beamwidth is 2.7 degrees at the 3 db points. A 100-foot aerial tower, shown in Figure 1, was used to position the radiometer at different heights and depression angles, with respect to the target.

Differing amounts of obscuration were attained by positioning the radiometer, moving the target and removing foliage. The target used was a 16 square-foot metal plate. It was painted yellow and positioned at 30 degrees with respect to the horizon to ensure that it reflected

35 GHz TRACKING AND MEASUREMENT RADIOMETER K.S.D. NO. 401
 MODIFIED TO OPERATE IN DICKE MODE BY B.R.L.
 $\Delta T_{\text{MIN.}} = 0.4^\circ \text{K}$ (.3 SEC. POST DETECTION INTEGRATION)
 ANTENNA B.W. = 2.7° AT 3db POINTS

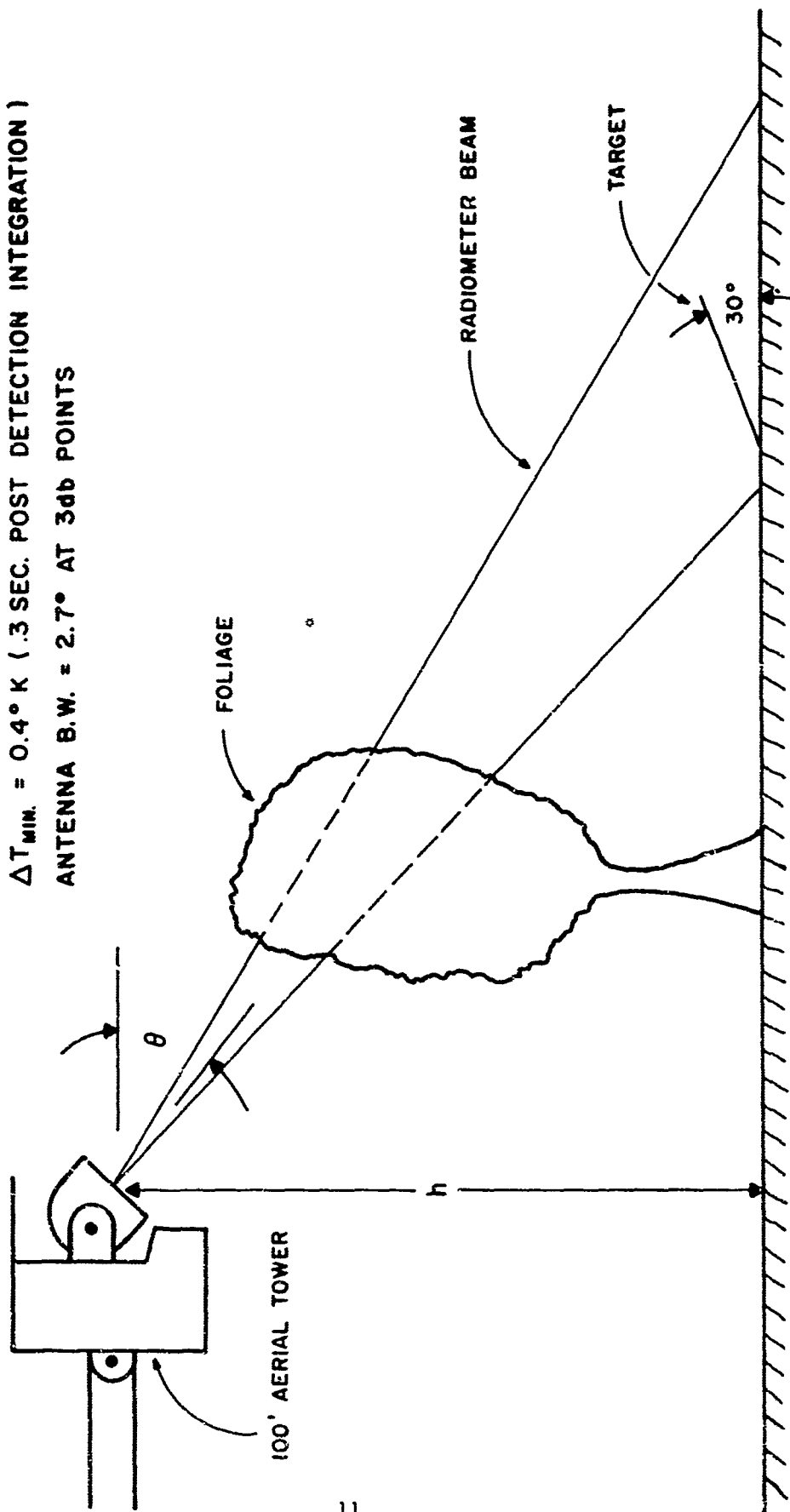


FIGURE 1 - TEST AND MEASUREMENT SETUP

the coldest portion of the sky near the zenith. For each test position, a 35-mm color photograph was taken of the painted target to provide an optical contrast. Optical blockage was determined from the photograph.

A black body source at a known temperature was used to calibrate the radiometer. The black body consisted of a microwave absorber maintained at a uniform temperature by uniformly heated circulating air. The system was calibrated before and after each measurement to check radiometer stability. In most cases, the target did not fill the radiometer beam. A beam-filling factor was determined by repeating each measurement without foliage.

The measurement procedure consisted of the following steps for each position and amount of obscuration:

1. Calibrate radiometer with black body.
2. Photograph target through foliage.
3. Measure radiometric temperature of target obscured by foliage.
4. Remove target and measure radiometric temperature of background.
5. Record height and depression angle of radiometer.
6. Place target in the open with no obscuration.
7. Measure radiometric temperature of open target.
8. Photograph open target.
9. Remove target and measure background temperature.
10. Recalibrate radiometer with black body.

IV. FIELD MEASUREMENTS AND DATA REDUCTION

A total of 46 measurements were made on two dates, 26 June and 31 July 1967, at Spesutie Island, Aberdeen Proving Ground, Maryland. The zenith sky temperature was 30°K and the ambient temperature (thermal) ranged between 294°K and 303°K . The data are tabulated in Table I.

Table I. Data and Results

DATE: 26 June 1967										
Plate No.	T_m , (°K) Radiometric Temperature of Obscured Plate	T_B , (°K) Radiometric Temperature of Background	H , (ft) Height of Radiometer above target	θ , (°) Depression Angle, Horizon to Target	E Beam Filling Factor	B Radiometric Blockage	B' Optical Blockage	R/R' Range Red. Factor		
1	257.6	273.2	47	42	.797	.92	.86	.282		
2	242.8	273.8	45	38	.774	.836	.74	.405		
3	264.1	267.0	44	39	.795	.985	.94	.126		
4	249.2	269.0	44	36	.779	.894	.93	.326		
5	229.2	271.7	44	38	.779	.746	.82	.504		
6	260.0	277.6	44	35	.735	.903	.84	.311		
7	267.4	270.3	44	30	.639	.982	.92	.134		
8	260.6	271.3	44	36	.779	.943	.84	.239		
9	258.5	272.5	44	38	.727	.921	.83	.281		
10	263.1	268.8	40	28	.630	.961	.85	.197		
11	250.7	270.5	40	28	.630	.869	.77	.362		
12	269.6	270.0	33	25	.619	.997	.97	.055		
13	264.3	270.8	37	28	.628	.957	.83	.207		
14	271.2	272.0	44	34	.727	.997	.93	.071		
15	81.8	284.7	47	42	.797	.0	0	1		
16	87.9	286.8	45	38	.774	0	0	1		
17	82.8	287.4	44	39	.795	0	0	1		
18	86.9	286.9	44	36	.779	0	0	1		
19	99.2	283.7	44	34	.727	0	0	1		
20	120.7	288.4	44	30	.649	0	0	1		
21	98.2	286.8	44	35	.735	0	0	1		
22	123.8	283.7	40	28	.630	0	0	1		
23	125.8	281.6	33	25	.619	0	0	1		
24	121.7	283.7	37	28	.638	0	0	1		

* Measured data, not calculated

Table I. Data and Results (Continued)

Plate No.	* T_m ($^{\circ}\text{K}$) Radiometric Temperature of Obscured Plate	* T_B ($^{\circ}\text{K}$) Radiometric Temperature of Background	* H_r (ft) Height of Radiometer above target	* θ_r ($^{\circ}$) Depression Angle Horizon to Target	E Beam Filling Factor	B Radiometric Blockage	B' Optical Blockage	R/R ₀ Range Red.
1	216.2	275.0	39	30	.706	.660	.37	.583
2	170.9	276.0	39	28	.645	.338	.24	.813
3	218.6	273.8	39	28	.645	.649	.25	.592
4	201.4	273.8	39	26	.611	.514	.21	.697
5	153.4	276.6	39	30	.706	.292	.19	.841
6	247.2	273.8	39	32	.713	.847	.66	.391
7	248.0	276.6	39	30	.706	.836	.37	.405
8	223.4	278.0	39	30	.706	.688	.25	.558
9	229.0	279.4	39	34	.747	.729	.38	.520
10	173.0	276.0	39	30	.706	.407	.22	.770
11	216.4	276.0	39	28	.645	.624	.32	.613
12	142.2	273.8	35	34	.790	.317	.26	.826
13	153.4	278.3	35	34	.790	.363	.30	.798
14	128.2	276.6	35	28	.669	.100	.19	.948
15	119.8	277.0	35	28	.669	.049	.09	.975
16	128.2	282.2	39	26	.611	.0	0	1
17	119.8	283.0	39	28	.645	0	0	1
18	104.4	233.0	39	30	.706	0	0	1
19	103.0	284.2	39	32	.713	0	0	1
20	114.2	284.2	35	28	.669	0	0	1
21	83.4	284.2	35	34	.790	0	0	1
22	94.2	284.2	39	34	.747	0	0	1

* Measured data, not calculated

The first step in reducing the data is the determination of the beam-filling factor. Under beam-filling conditions, the radiometric temperature of the target equals the sky temperature since the reflectivity is approximately unity at 35 GHz. Consider the non-beam-filling case as illustrated in Figure 2.

A portion of the background area, A_2 , is seen by the radiometer. The radiometric temperature, T_m , measured by the radiometer is higher than T_s because of emission by the background. The average power received by the radiometer is the sum of two quantities. One quantity is power received from the target which is proportional to T_s times A_1 . The other quantity is the power received from the background which is proportional to T_B times A_2 . The total average power received by the radiometer is proportional to T_m times $(A_1 + A_2)$.

$$T_m(A_1 + A_2) = T_s A_1 + T_B A_2 \quad (4)$$

$$T_m = T_s \left(\frac{A_1}{A_1 + A_2} \right) + T_B \left(\frac{A_2}{A_1 + A_2} \right) \quad (5)$$

Define $E = \frac{A_1}{A_1 + A_2}$ the beam-filling factor.

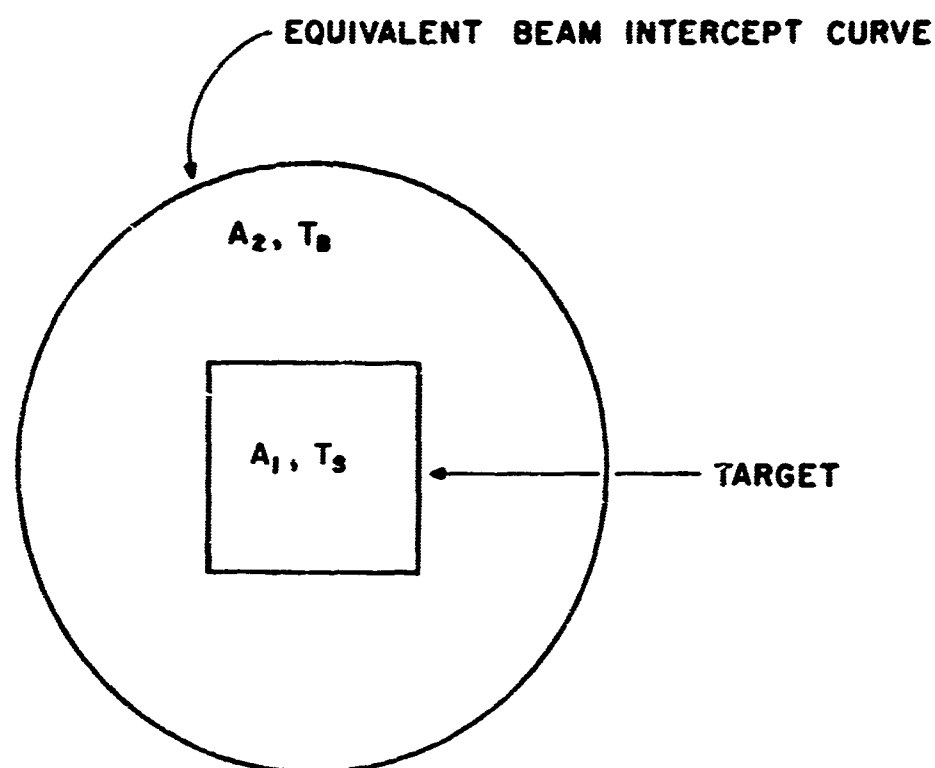
$$T_m = E T_s + (1 - E) T_B \quad (6)$$

Solve for E

$$E = \frac{T_B - T_m}{T_B - T_s} \quad (7)$$

All the factors on the right hand side of Equation (7) are determined from the unobscured reflector data.

Optical obscuration is determined from the color photographs of the obscured target. The photograph is projected on cross-sectional graph paper. From this projection the ratio of the target area obscured to the total target area is computed. This ratio is defined as the optical blockage (obscuration), B' .



A_1 = AREA OF TARGET

T_s = RADIOMETRIC TEMPERATURE OF TARGET

T_b = RADIOMETRIC TEMPERATURE OF BACKGROUND

$A_1 + A_2$ = TOTAL AREA SUBTENDED BY RADIOMETER BEAM

FIGURE 2 - MODEL FOR DETERMINATION OF
BEAM FILLING FACTOR

Radiometric blockage, B, is computed using the model shown in Figure 3. The average power received by the radiometer consists of three quantities as follows:

$T_s A_{11}$ = Average power received from A_{11} .

$T_B A_{12}$ = Average power received from A_{12} .

$T_B A_2$ = Average power received from the background.

$T_m (A_1 + A_2)$ = Total average power received by radiometer.

$$T_m (A_1 + A_2) = T_s A_{11} + T_B A_{12} + T_B A_2 \quad (8)$$

$$T_m = T_s \left(\frac{A_{11}}{A_1 + A_2} \right) + T_B \left(\frac{A_{12}}{A_1 + A_2} \right) + T_B \left(\frac{A_2}{A_1 + A_2} \right) \quad (9)$$

$$T_m = T_s \frac{A_{11}}{A_1} \left(\frac{A_1}{A_1 + A_2} \right) + T_B \frac{A_{12}}{A_1} \left(\frac{A_1}{A_1 + A_2} \right) + T_B \frac{A_2}{A_1 + A_2} \quad (10)$$

The quantity $\frac{A_1}{A_1 + A_2}$ was previously defined as E, the beam-filling factor. It follows that $1 - E = \frac{A_2}{A_1 + A_2}$. Define $B = \frac{A_{12}}{A_1} = \frac{\text{Obscured area of target}}{\text{Total area of target}}$. Substituting E and B into Equation (10),

$$T_m = T_s (1 - B) E + T_B B E + T_B (1 - E) \quad (11)$$

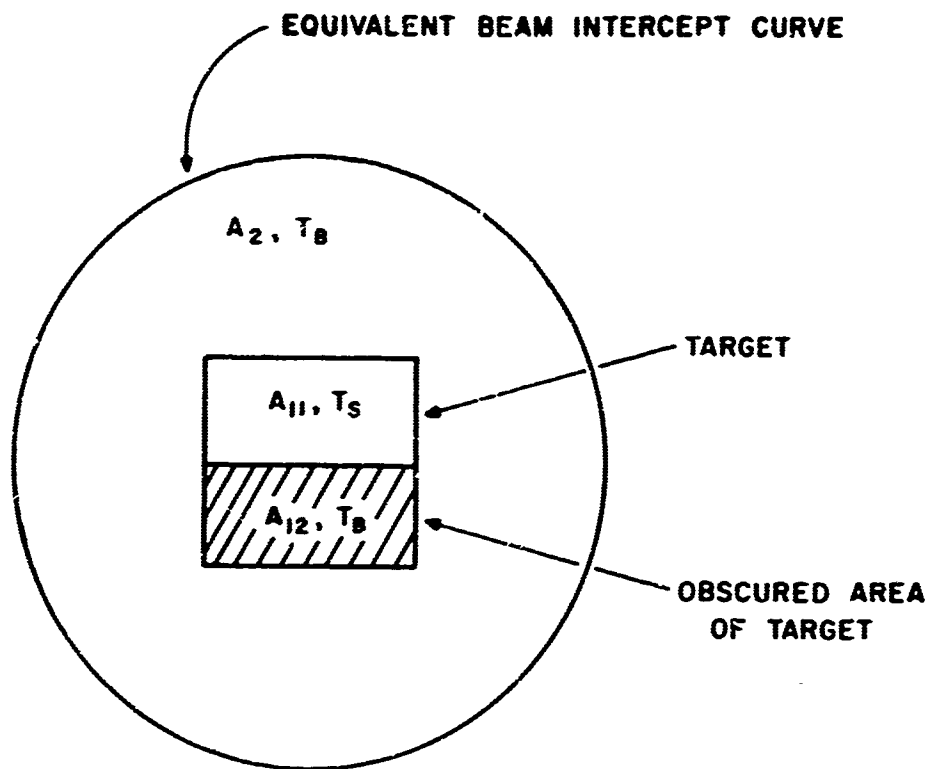
Solve Equation (11) for B,

$$B = \frac{T_m - E T_s - (1 - E) T_B}{E (T_B - T_s)} \quad (12)$$

Each term in Equation (12) is known or computed from the data; therefore, B can be evaluated for each measurement.

V. RESULTS AND DISCUSSION

Figure 4 is a graph of B (radiometric blockage) versus B' (optical blockage). In general, the radiometric blockage is higher than the optical blockage. A linear least-squares approximation was fitted to the



$A_{11} + A_{12} + A_2 = \text{TOTAL AREA SUBTENDED BY RADIOMETER BEAM}$

$A_{11} = \text{OPEN AREA OF TARGET AT TEMPERATURE } T_s$

$A_{12} = \text{OBSCURED AREA OF TARGET AT TEMPERATURE } T_B$

$A_2 = \text{AREA OF BACKGROUND AT TEMPERATURE } T_B$

$A_{11} + A_{12} = A_1, \text{ THE AREA OF THE TARGET}$

**FIGURE 3 - MODEL FOR DETERMINATION OF
RADIOMETRIC BLOCKAGE**

$$(B \text{ ON } B') \quad B = .842 B' + .216 \quad S_{B, B'} = .15$$

$$(B' \text{ ON } B) \quad B = 1.050 B' + .097 \quad S_{B', B} = .15$$

————— B ON B'
 - - - - - B' ON B

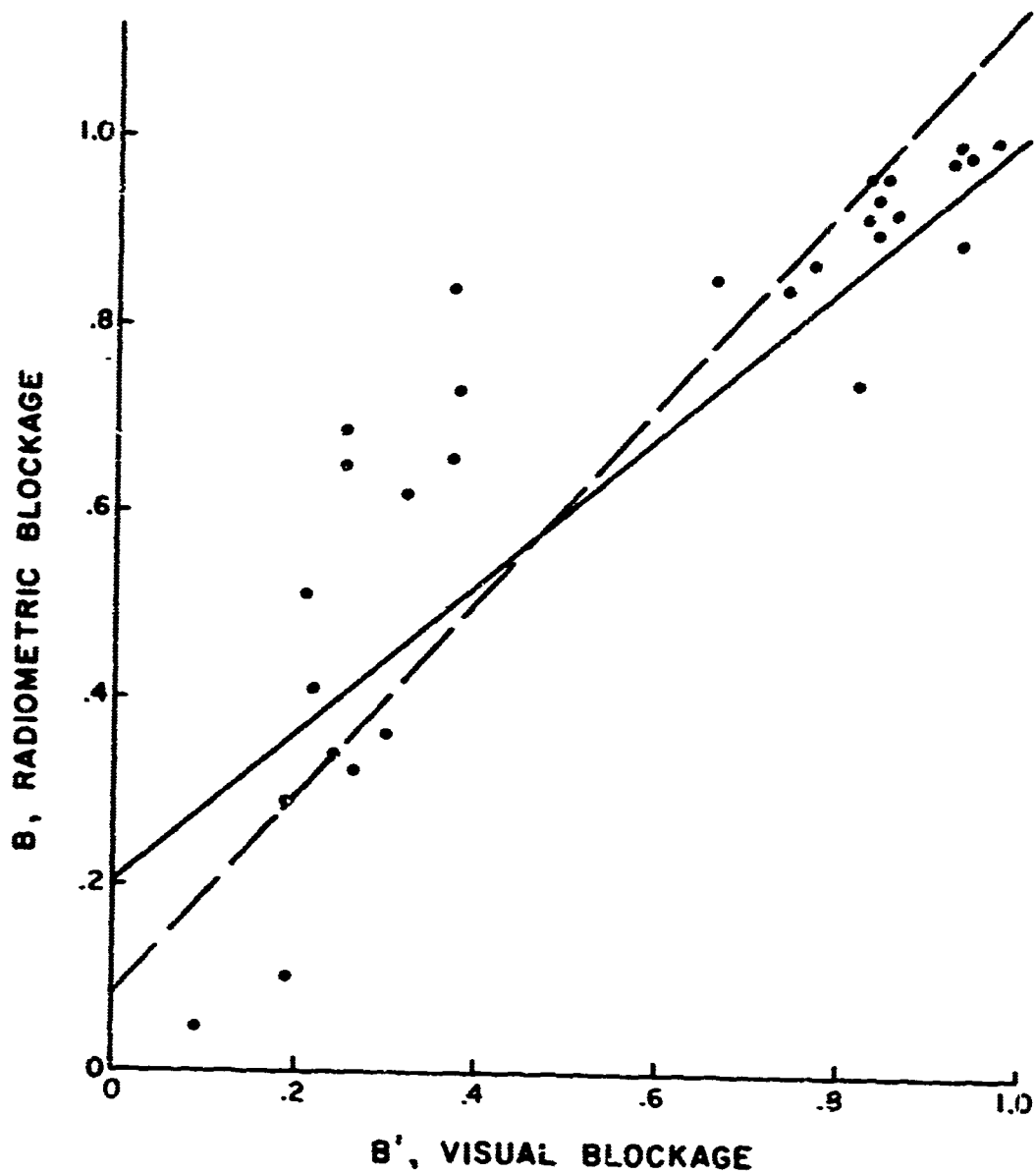


FIGURE 4 - LINEAR LEAST SQUARES FIT.
 RADIOMETRIC BLOCKAGE VS
 VISUAL BLOCKAGE

data. The linear regression of B (the dependent variable) on B' (the independent variable) is $B = 0.842B' + 0.216$, which has a standard error, $S_{B,B'}$; equal to 0.15. If the dependent and independent variables are interchanged, the linear regression line for B' on B is $B' = 1.05B + 0.097$ with $S_{B',B} = 0.15$. The two regression lines in Figure 4 are not the same. This is to be expected since the computed correlation factor was + 0.88. If the data were perfectly correlated and a linear relationship existed between the variables, then the two regression lines would be coincident. In order to achieve a better fit to the data two curvilinear fits were also used. An exponential curve was fitted yielding $B = 1 - 1.55e^{-4.18B'}$ for B on B' with a standard error $S_{B,B'} = 0.145$. With B' on B, the relationship is $B' = 0.0988e^{2.217B}$ with $S_{B',B} = 0.165$. The exponential fit, shown in Figure 5 has approximately the same standard error as the linear fit. A quadratic curve was also fitted to the data, yielding the relationship $B = -0.02 + 1.94B' - 0.923(B')^2$, with B as the dependent variable and B' as the independent variable. The standard error is $S_{B,B'} = 0.1177$. For B' on B, we get $B' = 0.103 + 1.59B - 0.7(B)^2$ with $S_{B',B} = 0.1178$. These curves are shown in Figure 6. The quadratic curves yielded a better fit than the exponential or linear fits. Also, the two curves derived by switching dependent and independent variables match very well. A higher degree polynomial fit would not be considered useful for an empirical relationship, at least not until a more sophisticated model is derived. We may conclude, therefore, that the optical blockage and radiometric blockage appear to be related quadratically rather than linearly.

When evaluating the performance of a radiometric system, the range reduction factor in the foliage situation is used. This factor is derived as follows. From the radiometer range Equation (3)

$$R_o^2 = kA \quad (13)$$

where k is a proportionality factor A = area of the target, R_o = range for open target. If the target is obscured by a factor B, then the visible portion of the target is $A(1 - B)$. The theoretically obscured range, R, is determined by

$$(B \text{ ON } B') \quad B = 1 - 1.55 e^{-4.18 B'} \quad S_{B, B'} = .145$$

$$(B' \text{ ON } B) \quad B = .0988 e^{2.217 B'} \quad S_{B', B} = .165$$

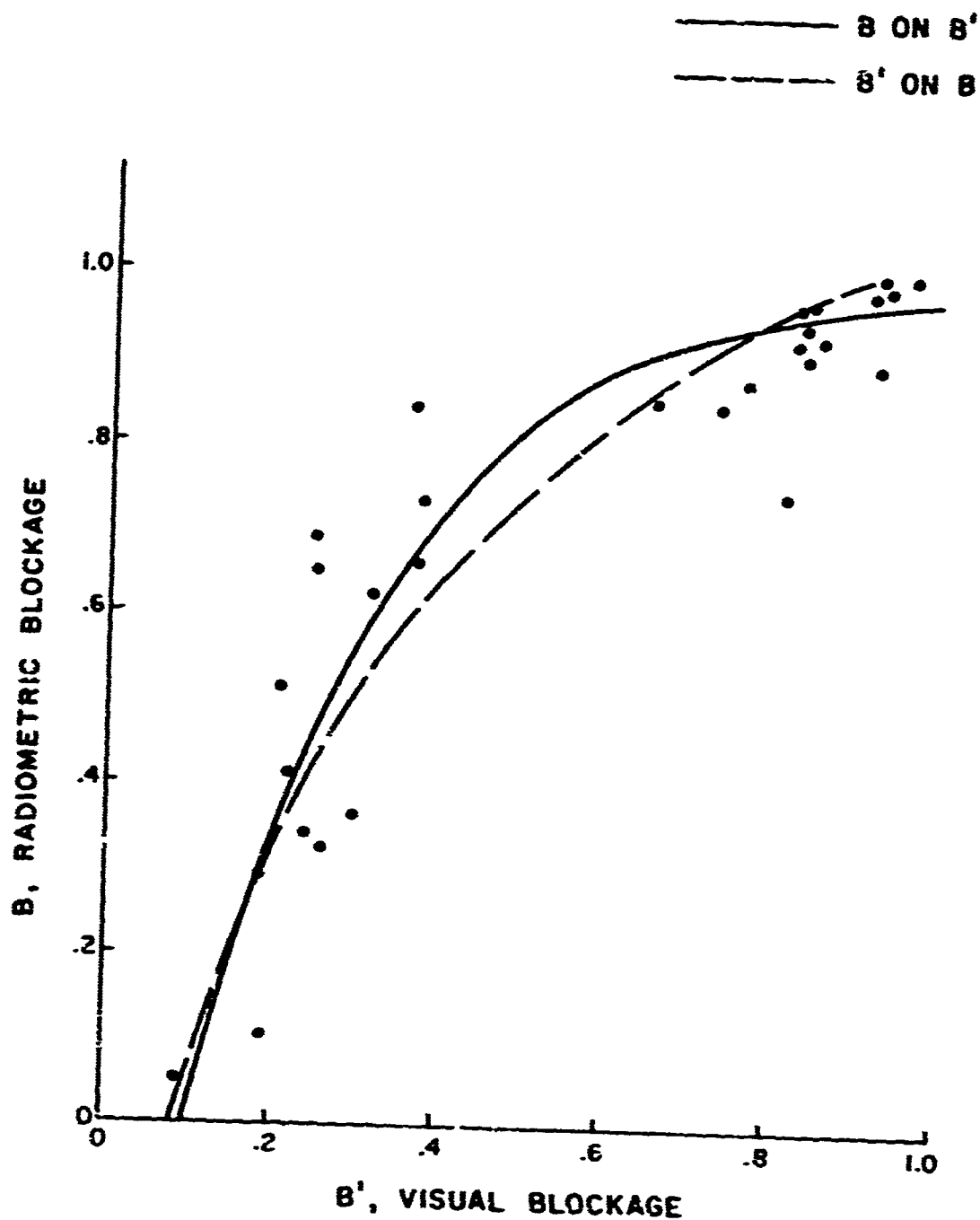


FIGURE 5 - EXPONENTIAL LEAST SQUARES FIT.
RADIOMETRIC BLOCKAGE VS
VISUAL BLOCKAGE

$$(B' \text{ ON } B) \quad B = -.02 + 1.94 B' - .923 (B')^2 \quad S_{B', B} = .1177$$

$$(B \text{ ON } B') \quad B = .103 + 1.59 B' - .700 (B')^2 \quad S_{B, B'} = .1178$$

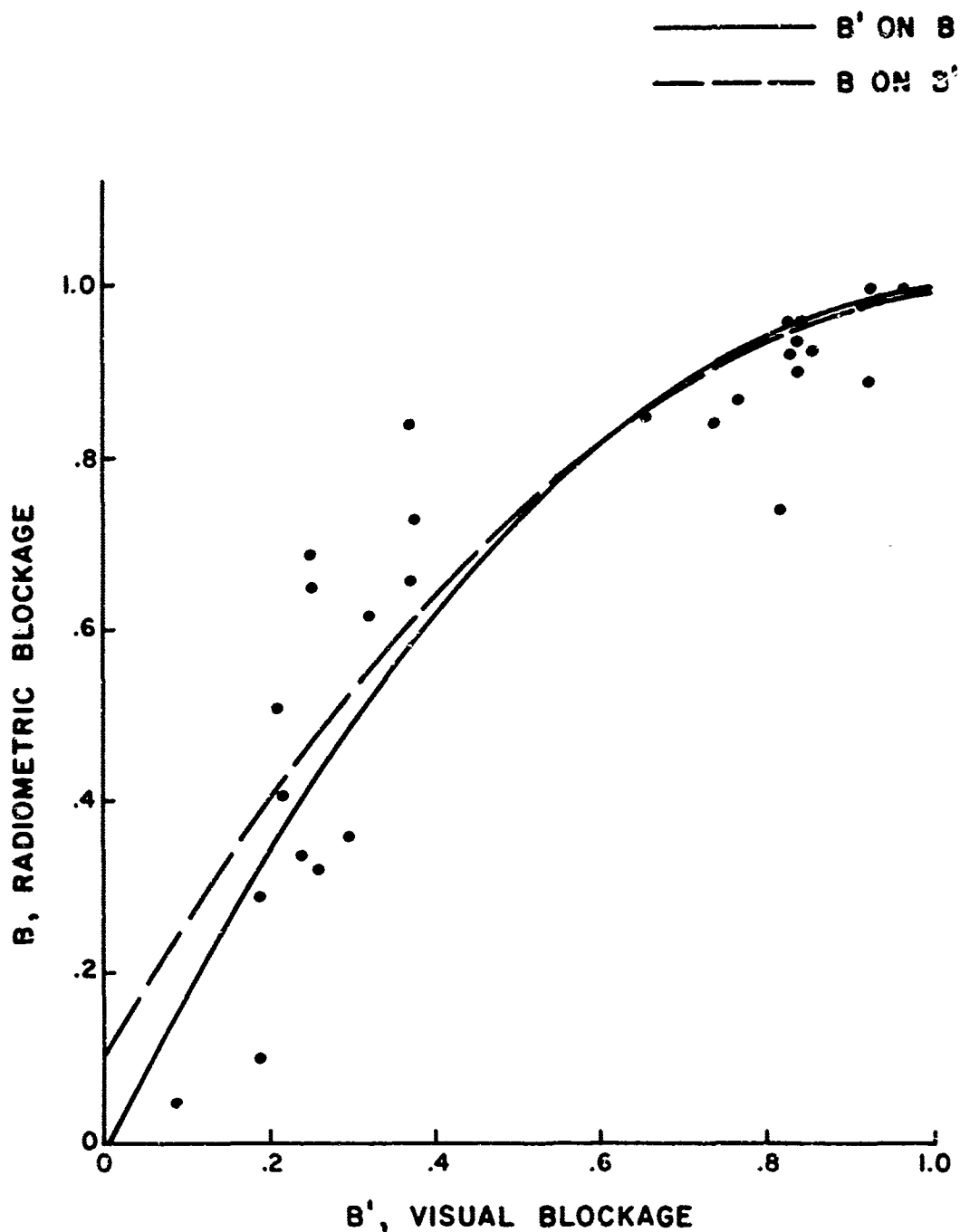


FIGURE 6 - QUADRATIC LEAST SQUARES FIT.
RADIOMETRIC BLOCKAGE VS
VISUAL BLOCKAGE

$$R^2 = kA(1 - B) \quad (14)$$

$$\frac{R^2}{R_0^2} = \frac{kA(1 - B)}{kA} = 1 - B \quad (15)$$

Figure 7 shows $\frac{R}{R_0} = \sqrt{1 - B}$ versus B' . Since B and B' are related quadratically, then $\frac{R}{R_0}$ should be related linearly with B' . A least-squares linear fit was calculated yielding the following relationship for $\frac{R}{R_0}$ on B' : $R/R_0 = -0.837B' + 0.947$, $S_{R/R_0, B'} = 0.112$. For B' on R/R_0 : $R/R_0 = -0.961B' + 1.01$, $S_{B', R/R_0} = 0.115$. $\frac{R}{R_0}$ appears to be best approximated by a linear relationship to B' .

The spread in the data tends to indicate that a better model is needed. At least three points of refinement may be considered. First, the foliage may not have the same radiometric temperature as the background. Leaf temperature may vary depending on the orientation of the leaves, their emissivity and reflectivity. Second, the radiometric temperature of the branches may be different from that of the background. Third, the effect of diffraction may not be properly accounted for because the foliage has depth and is not a thin mask as in the original model. These problem areas should be examined individually and a better model derived.

In summary, the radiometric penetration of foliage is a difficult problem to model and to study, especially in the area of repeatability of measurements. Despite the measurement difficulties, however, our investigations show that radiometric blockage and optical blockage are related quadratically. Hence, the range reduction factor is related linearly to optical blockage.

$$(R/R_0 \text{ ON } B') \quad R/R_0 = -.837 B' + .947 \quad S_{R/R_0, B'} = .112$$

$$(B' \text{ ON } R/R_0) \quad R/R_0 = -.961 B' + 1.010 \quad S_{B', R/R_0} = .115$$

————— R/R_0 ON B'
 - - - - - B' ON R/R_0

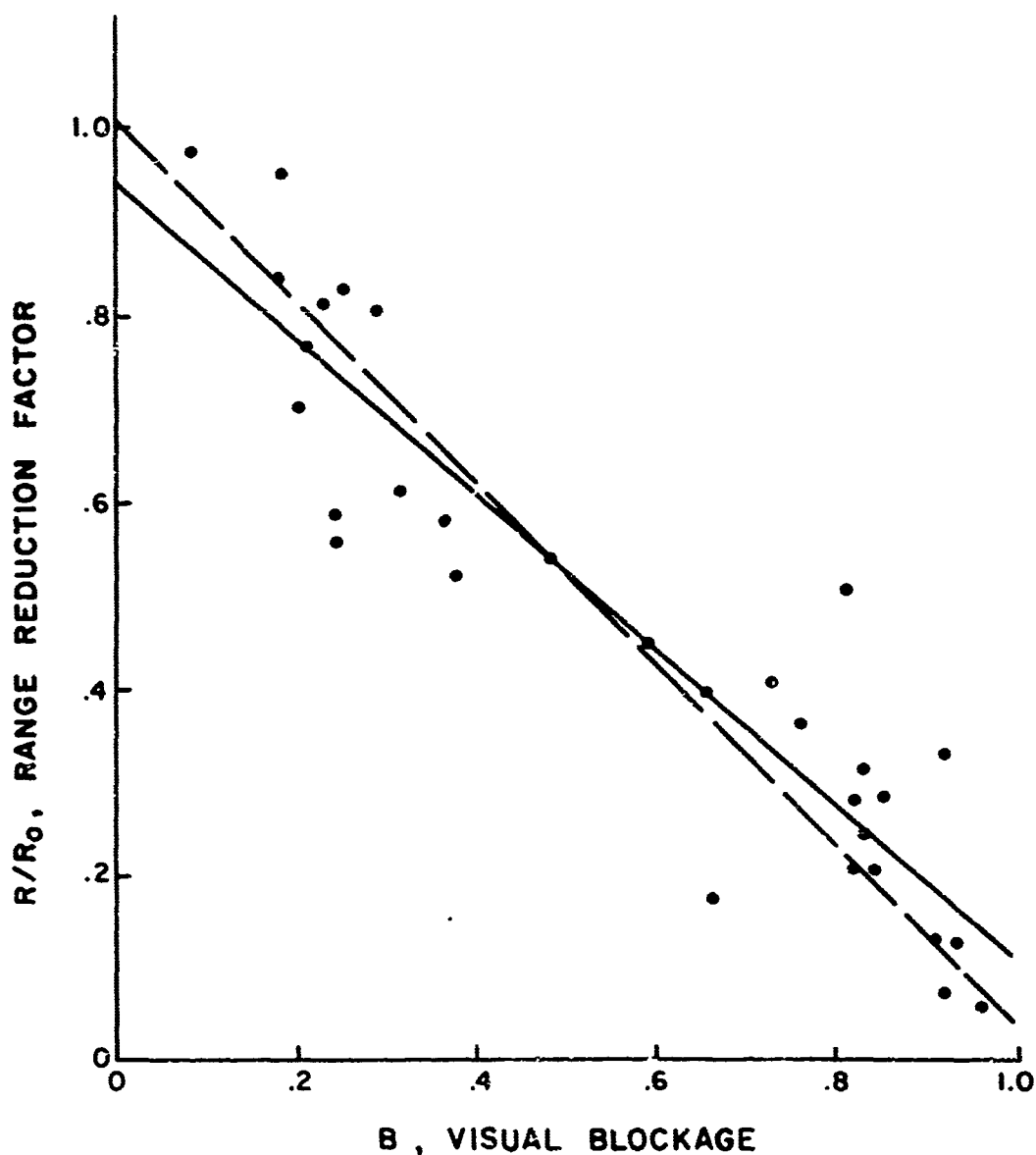


FIGURE 7 - LINEAR LEAST SQUARES FIT.
 RANGE REDUCTION FACTOR
 VS VISUAL BLOCKAGE

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

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1. ORIGINATING ACTIVITY (Corporate author) U.S. Army Ballistic Research Laboratories Aberdeen Proving Ground, Maryland		2a. REPORT SECURITY CLASSIFICATION Unclassified	
		2b. GROUP	
3. REPORT TITLE MILLIMETER WAVE RADIOMETRIC DETECTION OF TARGETS OBSCURED BY FOLIAGE			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)			
5. AUTHOR(S) (First name, middle initial, last name) Richard A. McGee			
6. REPORT DATE January 1968		7a. TOTAL NO. OF PAGES 28	7b. NO. OF REFS
8a. CONTRACT OR GRANT NO.		8b. ORIGINATOR'S REPORT NUMBER(S) Memorandum Report No. 1901	
a. PROJECT NO. RDT&E 1M523801A286			
c.		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
d.			
10. DISTRIBUTION STATEMENT This document has been approved for public release and sale; its distribution is unlimited.			
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY U.S. Army Materiel Command Washington, D.C.	
13. ABSTRACT The problem of passive detection by millimeter wave radiometry of metallic targets obscured by foliage and other vegetation is defined and discussed. A model of the foliage obscuration situation is presented and evaluated on the basis of data collected in a field measurement program. Results obtained show the millimeter wave radiometric obscuration to be greater than the optical obscuration. Curve fitting techniques indicate a quadratic relationship between radiometric and optical obscuration; hence, the maximum range of a radiometric system will be reduced linearly with optical obscuration instead of theoretically with a square root relationship. Further refinements of the model are discussed and are to be included in a general foliage penetration model to be evaluated at a later date.			

DD FORM 1473

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Unclassified

Security Classification

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Millimeter Wave Radiometry Passive Detection Obscured Targets						

Unclassified
Security Classification